Early-age responses of railway prestressed concrete sleepers to creep and shrinkage

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Early-age responses of railway prestressed concrete sleepers to creep and shrinkage

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ABSTRACT

Prestressed concrete have been commonly used for manufacturing railway sleepers since 1940s because of many superior advantages in high endurance performance, maintainability, sustainability, and construction resilience. Prestressed concrete has overcome the low tensile strength in concrete by introducing a prestressing force along the high-strength steel tendons/wires to enable cross sectional compression. However, the short-term performance of prestressed concrete members largely depends on creep and shrinkage responses at early age. The effects of time-dependent phenomena on prestressed concrete sleeper are investigated in this paper. In the past, many investigators had proposed various material models to predict creep and shrinkage but those applications were mostly based on general reinforced concrete concept. The popular uses of prestressed concrete have led to a concern of practitioners whether quality control of concrete at early age should also be focussed. Due to high initial elastic shortening in prestressed concrete, the creep and shrinkage effects at early age plays a critical role over the longer term performance. This study investigates and compares a variety of methods to evaluate creep and shrinkage effects in railway prestressed concrete sleepers. Comparison between design codes of European Standard EUROCODE2, American Standard ACI, and Australian Standard AS3600-2009 provides the insight into the time-dependent performance of railway concrete sleepers. The outcome of this study will help railway and structural engineers to better design and control early age quality of concrete sleepers, improving their life expectancy.

Keywords: creep; shrinkage, elastic shortening, prestress losses, prestressed concrete, railway sleepers, crossties, Eurocode, ACI; AS3600-2009.

1. INTRODUCTION

First established back in 1820s, rail transport was critical to the Industrial Evolution and the development of economies. Nowadays, railway transportation system has become very important for both of passengers and freight transportation. It provides a highly enjoyable ride for passengers or freight. Railways are an essential transportation system to many countries around the world. Maintaining its design geometry over their operational life and a continuous service, with minimal interruptions to maintenance is a challenge to railway engineering and extremely necessary to guarantee safety and economic efficiency [1-6]. Throughout the world, a railway track supported by ballast is widely accepted for conventional railway lines due to its advantages as inexpensive implementation costs and easy maintenance [6-11]. Ballasted railroad track infrastructure is a layered system essentially comprised of two main parts: superstructure and substructure as shown in Figure 1. The superstructure includes the main load-supporting elements of the track; it is basically constituted of rails, the fastening systems, sleepers and ballast. The substructure is related with the geotechnical system comprising the sub-ballast and subgrade or formation.

Railway sleepers (or called 'railroad ties' in North America) are the main element of rail track structure. The main functions of railway sleepers are:

- To support rail and maintain the track gauge.
- To distribute loads to substructure.

Materials employed in sleepers can be timber, steel, concrete and any other engineered materials. After the Second World War, the use of concrete sleepers had a significant increase in Britain and Europe due to the timber scarcity. Progressively, reinforced and pre-stressed concrete sleepers have replaced timber and steel sleepers [12] due to their prolonged life cycle and reduced maintenance costs [13-16]. Two varieties of concrete sleepers are offered in the market accordingly to Esveld [7]: reinforced twin-block and prestressed monoblock sleepers. The twin-block consists of two blocks of reinforced concrete connected by a steel bar or stiff steel beam. While monoblock sleepers consist of one prestressing reinforced concrete beam [17-19]. Monoblock concrete sleeper is the type that has greater acceptance in the market due to its superior durability in the face of unfavourable environments. Another advantage observed is the resistance to twist, failure commonly presented by twin block concrete sleepers. Because of this usual failure the installing process of this type of sleeper requires greater care, making it more difficult to handle and contributing to a lower acceptance, even with their reduced weight compared to monoblock sleepers.

Concrete is known for its high resistance to compression, on the other hand, presents weakness when it comes to tension. Prestressed concrete sleepers are most commonly used type of sleeper around world. Due to this characteristic, monoblock concrete sleepers use the technique of prestressing to withstand the dynamic loads arising from the passage of the train. This procedure consists of the tensioning of steel rods before or after the concrete is moulded. Prestressed concrete presents increased ductility, higher flexural strength and resistance to cracking [18]. The stability and slight position movement offered by prestressed concrete sleepers because of its heavy weight meant that it had a significant acceptance in high-speed lines. At the same time, the great weight reduces mobility, making it difficult to transport and being necessary specific equipment for installation which increases the costs of concrete sleepers. One of the causes of this high weight is a need for greater thicknesses in comparison to timber sleepers with the aim of reducing dynamic tension at the bottom fibre [20]. Costs for producing and maintaining prestressed concrete sleepers are considerably elevated. Their initial costs are about twice that the hardwood timber sleepers [16]. However, due to its high durability and specifications that comply with the solicitations of a railway system, prestressed concrete sleepers can be currently considered as the best cost-benefit to serve ballasted railway lines [20] and the preferred sleeper to railway tracks nowadays [8].

Prestressed concrete sleepers have been developing for decades with long life cycle, low maintenance cost and good structural performance in comparison with reinforced concrete sleepers. Prestressed concrete sleepers are expected to withstand high dynamic loads and harsh environments. However, concrete structure, owing to its material property, is deforming with time which is risky from creep and shrinkage. Time-dependent behaviours can result in deformation, crack and loss of prestress to cause potential risks for trains using the sleepers. Therefore, prediction of time-dependent behaviours becomes essential when considering serviceability limit state [20]. This paper presents the influence of early age characteristics on the time-dependent behaviours of prestressed concrete sleepers. In addition, European and Australian design methods [20, 21] will be used to compare.

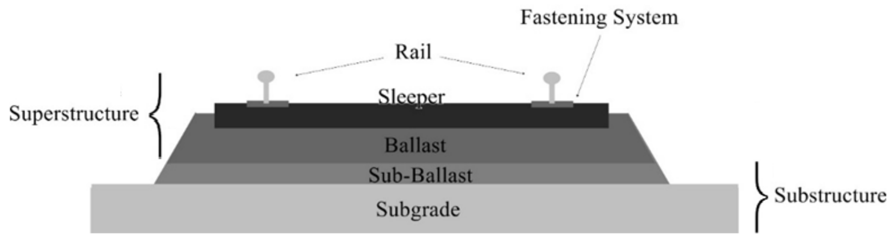


Figure 1 Schematic Track Structure

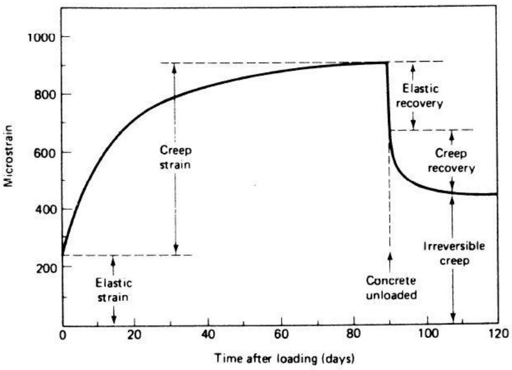
2. CREEP AND SHRINKAGE

Railway prestressed concrete sleepers are often designed for 50 year service life. Therefore, its serviceability condition over time becomes very essential in track maintenance. The creep and shrinkage of concrete play a key role in serviceability of the railway sleepers. The creep and shrinkage continually change with time and they respond to early age behaviour of the concrete component.

2.1 Creep

The concrete under sustained load whose strain increases with time is due to creep. Therefore, creep can be defined as the increase in strain under the sustained stress and it can be several times as large as the initial strain. Creep is a considerable factor in concrete structure. The deformation of concrete is different from other materials like steel. When a load is applied to steel, the deformation won't change with time if the load is constant. Concrete deforms as soon as the load applied like steel. This is known as elastic deformation. However, the displacement of concrete gradually increases with time when the load left in place. The displacement reaches a value as large as three to four times of immediate elastic deformation. The inelastic deformation with constant load is known as creep deformation. "Creep is defined as the increase of strain with time when the stress is held constant."[20]. As the rule, creep increases when water/cement ratio increases or cement content increases. On the other hand, creep decreases when aggregate content increases in concrete mixture. Table 1 demonstrates the response prediction of creep.

Table 1. Creep response evaluation

Response	Eurocode 2 [20]	AS3600 [21]
total creep strain ε_{cc} (∞, t_0) of concrete	$\varepsilon_{cc}(\infty,t_0)=\varphi(\infty,t_0)\times\frac{\sigma_c}{E_c}$ $\varphi(\infty,t_0)=\varphi_{RH}\times\frac{16.8}{\sqrt{f_{cm}}}\times\frac{1}{(0.1+t_0^{0.20})}$ $\varphi_{RH}=1+\frac{1-0.01\times RH}{0.1+h_0^{0.333}},\quad f_{cm}\le 35MPa$ $\varphi_{RH}=(1+\frac{1-0.01\times RH}{0.1+h_0^{0.333}}\alpha_1)\alpha_2,\quad f_{cm}>35MPa$ $\alpha_1=(\frac{35}{f_{cm}})^{0.7},\quad \alpha_1=(\frac{35}{f_{cm}})^{0.2}\quad f_{cm}=f_{ck}+8MPa$ $t_0=t_{0,T}(\frac{9}{2+t_{0,T}^{1.2}}+1)^{\alpha}\ge 0.5,$ $\alpha=\{-1(S),0(N),1(R)\}$	creep coefficient at any time φ_{cc}: $\varphi_{cc}=k_2k_3k_4k_5\varphi_{cc.b}$ $k_2=\frac{\alpha_2(t-\tau)^{0.8}}{(t-\tau)^{0.8}+0.15t_h}$ $\alpha_2=1.0+1.12e^{-0.008t_h}$ $t_h=2A_g/u_e$ $k_3=\frac{2.7}{1+\log(\tau)}\ (for\ \tau>1\ day)$ $k_5=1.0\ when\ f'_c\le 50MPa$ $k_5=(2.0-\alpha_3)-0.02(1.0-\alpha_3)f'_c\ when\ 50MPa\le f'_c\le 100MPa$ $\alpha_3=0.7/(k_4\alpha_2)$
Note:	RH = relative humidity in %, h_0 = 2Ac/u mm, Ac = cross sectional area, u = perimeter of the member in contact with the atmosphere, S, R and N refer to different classes of cement.  	k_2 is the development of creep with time; k_3 is the factor which depends on the age at first loading τ (in days); k_4 is the factor which accounts for the environment; and k_5 is the factor which accounts for the reduced influence of both relative and humidity and specimen size. For the factor k_4 which accounts for the environment: $k_4=0.7\ for\ an\ arid\ environment$ $k_4=0.65\ for\ an\ interior\ enviroment$ $k_4=0.60\ for\ a\ temperate\ enviroment$ $k_4=0.5\ for\ a\ tropical\ or\ near-coastal\ enviroment$

2.2 Shrinkage

Both of creep and shrinkage are influenced by the same parameters. Shrinkage is not an entirely reversible process like creep and it can be also influenced by relative humidity, surface exposed to atmosphere, compressive strength of concrete and types of cement. Shrinkage can be divided by two parts:

- Plastic shrinkage: it happens in few hours after concrete placed.
- Dry shrinkage: evaporation leads to loss of water

According to, plastic shrinkage is due to water loss from concrete in plastic state. It could happen during the hydration process or water evaporation in environmental conditions. The factors lead to autogenous shrinkage is chemical reactions between water and cement known as hydration. There is not environmental influence such as temperature and moisture. Chemical reactions between carbon dioxide and the hydration products of cement leads to carbonation shrinkage. The carbonation chemical reaction equation is shown as $Ca(OH)_2+CO_2\rightarrow CaCO_3+H_2O$.

The effects of shrinkage include environmental condition, material properties, curing method and mix proportion. According to ACI, shrinkage is related to ratio of volume and surface area which shrinkage is inversely proportional to ratio of volume and surface area. Shrinkage $\propto\frac{1}{(\frac{V}{S})^2}$ where V is volume and S is surface area. Table 2 demonstrates the response prediction of shrinkage.

Table 2. Shrinkage response evaluation

Response	Eurocode 2 [20]	AS3600 [21]
total shrinkage strain ε_{cs}	$\varepsilon_{cs}=\varepsilon_{ds}+\varepsilon_{as}$	$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd}$ $\varepsilon_{cse} = \varepsilon'_{cse}(1.0 - \exp\{-0.1t\})$ $\varepsilon'_{cse} = (0.6f'_c - 1.0) \times 50 \times 10^{-6}\ (f'_c\ in\ MPa)$ $\varepsilon_{csd.b} = (1.0 - 0.008f'_c) \times \varepsilon'_{csd.b}$
Note:	ε_{ds} is drying shrinkage strain; and ε_{as} is autogenous shrinkage strain	ε_{cse} is autogenous shrinkage strain; ε_{csd} is drying shrinkage strain. Where $\varepsilon'_{csd.b}$ depends on the quality of the local aggregates and may be taken as 800×10^{-6} for concrete supplied in Sydney and Brisbane, 900×10^{-6} in Melbourne and 1000×10^{-6} in elsewhere. The drying shrinkage strain ε_{csd} after the beginning of drying $(t-\tau_d)$ can be estimated: $\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd.b}$ Where k_1 is the factor which describes the development of drying shrinkage with time; and k_4 is the factor which accounts for the environment

3. PRESTRESSED CONCRETE SLEEPERS

The early age behaviors of railway concrete sleepers are evaluated using the cross section shown in Figure 2. The fundamental engineering properties of prestressed concrete sleeper used for calculation are based on [1]. The results are generated for comparisons between Eurocode 2 (EC2) and Australian standard 3600-2009 (AS) [20-23]. The length of sleeper is 2700mm, track gauge is 1600mm, and nominal prestressing force is 550 kN. The rail cant is 1 in 20. It is found that the effect of rail cant on the early age responses is negligible or around 2% difference.

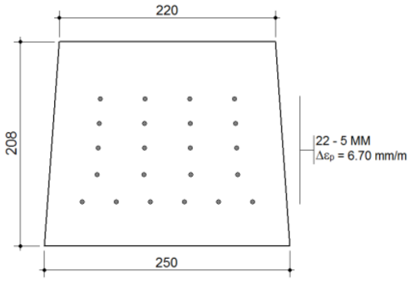


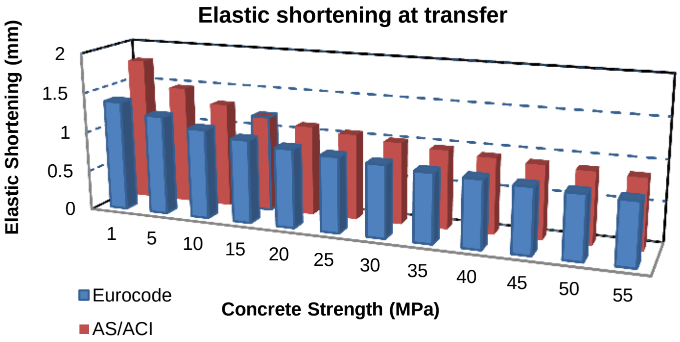
Figure 2 Cross section of a broad-gauge railway prestressed concrete sleeper

4. EARLY AGE RESPONSES

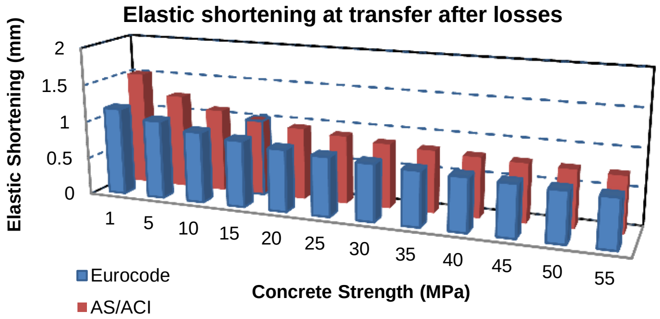
In general, railway prestressed concrete sleepers experience 2 stages of loading conditions. In manufacturing, the steam-cured sleeper is subjected to the pre-tensioned force at transfer (1 day after manufacturing). Then, the sleepers are transported to construction site and are installed on tracks (around 14-28 days after manufacturing). This implies that in practice, the concrete mix is sometimes overdesigned to ensure that the concrete gains 14-day strength over 55 MPa (prescribed). Early age responses of railway prestressed concrete sleepers can be determined as a combination of elastic shortening, creep and shrinkage. Figure 3 displays the effect of early age strength on the elastic shortening of sleeper at transfer. It can be observed that Eurocode slightly underestimate the shortening response of the sleeper at transfer in comparison with Australian or American standards (AS/ACI). Figure 3b shows the effect of steel relaxation loss of 15%.

Figure 4 illustrate the effect of creep and shrinkage on the time-dependent responses of railway concrete sleepers over service life. These behaviors are based on the nominal strength of concrete after 28 days. The results show that the initial or early age responses are critical to identify the serviceability over the service life of sleepers. If the early age characteristics of concrete are not achieved, the serviceability of sleepers will be significantly impaired.

For example, the shortening response will affect the rail gauge installation and the rail gauge overtime. The early age responses will affect the quality of rail gauge installation during railway construction. If the shortening is too high, the rail gauge can be fouled and additional work must be executed in order to commission safe train journey. In fact, if shortening overtime is excessive, trains could travel on a very tight gauge and incur hunting behavior, resulting in poor ride quality and excessive side wear of rails. If such condition is extreme, the wheel could potentially climb over the rail and cause derailments, especially on shallow curve tracks with slow-speed trains (static or slow speed trains generally run at relatively higher wheel-rail frictional coefficient compared with dynamic frictional coefficient or at higher speeds).



(a) before loss



(b) after steel relaxation of 15%

Figure 3 Elastic shortening at transfer of railway prestressed concrete sleeper

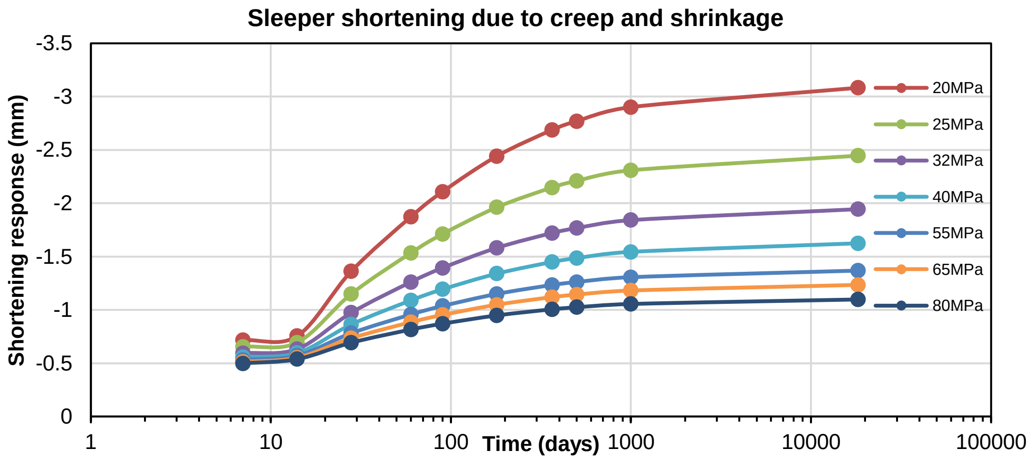


Figure 4 Time dependent responses of railway prestressed concrete sleeper (based on 28-day strength)

5. CONCLUSION

Railway prestressed concrete sleepers are structural and safety-critical components in railway track systems. Their time-dependent behaviours associated with early age responses have not been investigated elsewhere. This paper presents an unprecedented study into the early age responses, enabling a better understanding into longer term effects on the sleepers. The insight into sleeper shortening will help sleeper designers and manufacturers to re-assess and re-design the mold or the manufacturing bed so that the rail gauge can be within operational tolerance (e.g. +/- 4mm) under service. This knowledge will improve operational safety and reduce on-site correction work of rail installation. Such on-site rail repair could cause over €5m per kilometer of track.

6. ACKNOWLEDGEMENT

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